Modelling the effect of operating sluices on sediment deposition in a polder in southwest Bangladesh using MIKE 21 FM

Bachelor thesis
Davie Vuurboom
5719585

Earth Sciences
Faculty of Geosciences
Utrecht University

First supervisor: Prof. dr. Hans Middelkoop
Second supervisor: Md Feroz Islam

Universiteit Utrecht

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Abstract

As a result of the relative rise of the sea water level, polders in Bangladesh are prone to floodings. In the 1960 dykes where build to tackle floodings. However, these measures have only let to filling up the river since sediment was trapped in the riverbed. With the accompanying water level rise and a decrease in elevation within the polders in comparison with surrounding planes these new problems emerged. A Tidal river management (TRM) concept was developed to mitigate the water and sediment problems in this region.

The idea is simple: build sluices in the dykes so water with sediment can enter the polder. Then close the gates so the sediment has time to settle and accumulate and as last open the gates to let the water out.

In this thesis, the effect of sluices on sediment accumulation in polders in Bangladesh is researched. Specifically what kind of sluice (gate) operation is the most efficient to trap sediment in a polder. This is done by flooding a polder regulated in MIKE 21 FM, a 2D model. Three different seasons and three places along a river are investigated with six different kinds of gate operations. The results showed that the most efficient operation is depended on both the location in the delta and the season.

1. Introduction

The Ganges-Brahmaputra-Meghna (GBM) Delta in Bangladesh is a densely populated, low and flat coastal plain in South Asia. With a sediment discharge of over a billion tons, this delta has the biggest sediment load of the world (Milliman, 1983). Water levels in the delta are controlled by tides in the south, by the Bay of Bengal, and a fresh-water flow from the north through the rivers and their tributaries. The area is characterized by large tidal flats lying around 1 meter above sea level. Countless tidal creeks and channels distribute water through the landscape which makes Bangladesh prone to floods.

Until the 1960s, southwest Bangladesh was under the control of zamindars (landlords) who were responsible for providing embankments on the tidal flats in the dry season. However, during the monsoon, these low embankments got swept away by the floods. Water with sediment flooded the polders and renewed the land with nutrients and sediment. After the recession of the flood, new embankments would be constructed and the yearly cycle would be repeated. In the 1960s, the East Pakistan Water and Power Development Authority (EP-WAPDA) constructed 4000 km of embankments shifting the traditional local system to a Dutch inspired large-scale polders system. Since then, some polders have lost up to 1,5 m of elevation while neighbouring untouched mangrove forests have remained comparatively stable (Auerbach et al., 2015). Due to the relative sea level rise (RSLR), the risk for coastal and inland flooding is becoming a significant issue. Bangladesh has already been labelled as a 'delta in peril' (Rogers, Overeem, Chadwick, & Passalacqua, 2017). Because the sediment cannot escape the rivers due to the embankments, the rivers are silting up. Therefore, water levels in the rivers rise even further and increase the flood risk in the polders.

If nothing happens, polders will flood and the inhabitants of the polders will lose their houses and farms. Construction of polders, embankments and cross dams have been structural solutions for protecting the saline water from intruding the tidal plains but restricting the spreading of sediments due to the strong embankments.

An alternative option is a regulated tidal river management (TRM) concept based on the original zamindars' system. This is similar to the tidal river management showed in figure 1, but would be done by building sluices with gates in the embankments. This technique has been used before and has proven itself (van Staveren *et al.*, 2018). At high tide, the sluices can be opened and water with sediment can enter the polders regulated. Once the gates close the sediment will settle. When the water flows out of the polder the sediment will stay behind. This supports a rise of the ground level of the polders, brings in new nutrients for more productive agriculture and provides a decrease of water levels in the rivers due to the outflow of the sediments.

The goal of this thesis was to find out if TRM can help against the further decline of the area and at the same time resolve the silted up rivers and bring back nutrients to the polders. This was done by looking at the total sediment intake of the polders and in more detail how to operate the sluices in such a way that the most sediment is trapped and also

how it is spread homogeneously. Another aim was to find the best period to operate sluices so that farmers suffer the least as possible from the flooding inside the polder. An enlarged elevation of the polder is hypothesized due to the sediment supply inside the polder. The research is done by taking beel Pakimara, a polder in most south Bangladesh and placing it along a river so different regimes can be investigated. Data is put in a MIKE 21 FM 2D model which can calculate the total sediment accumulation and show the distribution of those sediments.

Figure 1 Controlled flooding in beels/polders with TRM in the Bangladesh delta. (Staverna et al., 2017)

2. Study area

2.1 Bangladesh

Bangladesh (figure 2) is located in South Asia. It is bordered on the west, north, and northeast by India and in the southeast by Myanmar and on the south by the Bay of Bengal. The land is covered by the Ganges-Brahmaputra-Meghna (GBM) rivers, and 80% are tidal flats. Surface elevations differ from less than 1 meter on tidal floodplains, to 1 to 3 meters on the main river and estuarine floodplains and up to 6 meters in the Sylhet basin in the northeast. The east part of the country is elevated with mountains up to 1000 meters above sea level. Bangladesh is economically underdeveloped.

The low level of development, combined with factors such as its geography and climate, makes the country vulnerable to climate change. With a population of over 164.7 million and a population density of 1211 persons per km^2, Bangladesh is a very densely populated country (World Bank, 2017). More than one-third (36%) of the people in Bangladesh live in poverty; in rural areas, it is 40%. About one-quarter of the country's GDP comes from agriculture which

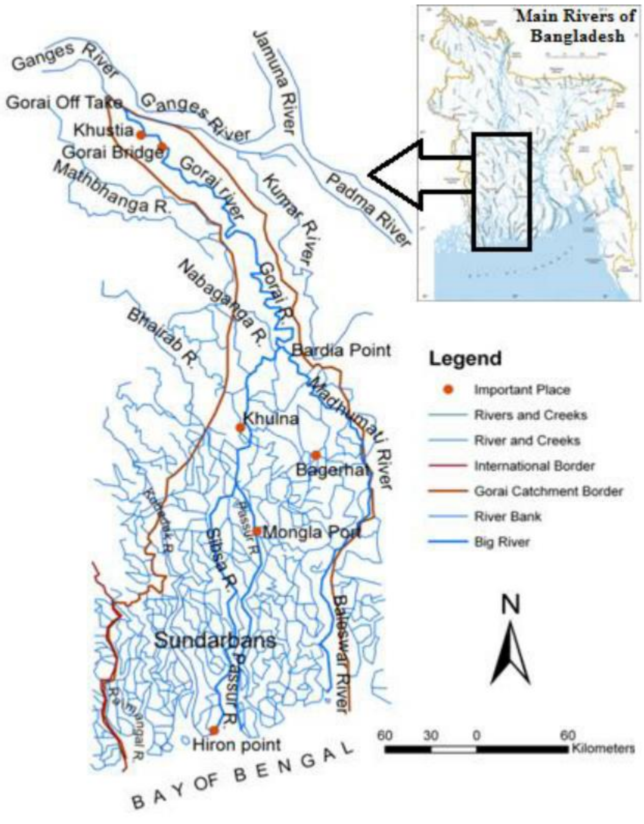

Figure 2 Southwest Bangladesh (modified after Islam and Gnauck, 2011)

makes the country's economy relatively sensitive to climate variability and change. (Argawala et al., 2003)

2.2 Tidal River Management

"*There may be two main reasons for the overflowing of river banks.* ***Firstly****, too much rainwater discharging too quickly.* ***Secondly****, the reduced holding capacities of the rivers and canals due to the continued siltation of their beds by the alluvial soil deposits carried by the water*." (Khalil, 1990)

The second reason is a consequence of the first reason. Until the 1960s southwest Bangladesh was under the control of Zamindars (landlords) who were responsible for providing embankments for the lands in the dry season. These earthen embankments protected the land from overflow in the dry seasons so farmers could grow crops. In the monsoon, these low embankments got swept away. Water with sediment flooded the polders and renewed the land with nutrients and sediment. After the recession of the flood new embankments would be constructed and the yearly cycle would be repeated. With this method the land was only agriculturally productive for some periods of the year but it kept the ecosystem in place.

When the Zamindars disappeared, the area was neglected. This resulted in disastrous floods in 1954, 1955 and 1956. To take measures against these floods the EP-WAPDA was created. Which later became the Bangladesh Water Development Board (BWDB). In the 1960s the EP-WAPDA constructed 4000 km of embankments shifting the traditional local system to a Dutch-inspired large-scale polders system. The short-term effects were positive: the area became agriculturally more productive. The strong embankments also gave an impression of safety and the population inside the polders increased rapidly.

In the 1970s a new kind of flooding emerged as mentioned in the second reason. Due to the embankments, silt in the rivers had nowhere to go which lead to silting up of the rivers. Water levels rose higher than the land within the embankments which caused the drainage network to congest and later to become waterlogged. Not only was this bad for the productivity but the gross of the hydro morphology was disrupted (Tutu, 2005). As a result, most of the sedimentation took place inside the channels. Now channel beds are rising in contrast with adjacent tidal plains.

2.3 Beel Pahkimara

The model that is used is set up for beel Pahkimara. The beel is 700 hectares in size and is in the Sathkhira district, southwest Bangladesh. Rivers which surround it are connected to the beel through a canal with a sluice in the southeast. and only a sluice in the northwest. More information about this beel can be found in *Islam, 2019.* In figure 3A-C pictures a shown from the beel to give an impression of the area.

Figure 3 Impressions of beel Pahkimara.

2.4 Study sites

Models were run on three different locations in a distributary channel of the Ganges in the southwestern part of the GBM delta. Upstream in the Gorai river (point 1), in the middle by Nabaganga (point 2) and downstream of the river Pussur (point 3). These three different spots had different water levels and suspended sediment concentrations which each had an effect on the total sedimentation in the polder (figure 4).

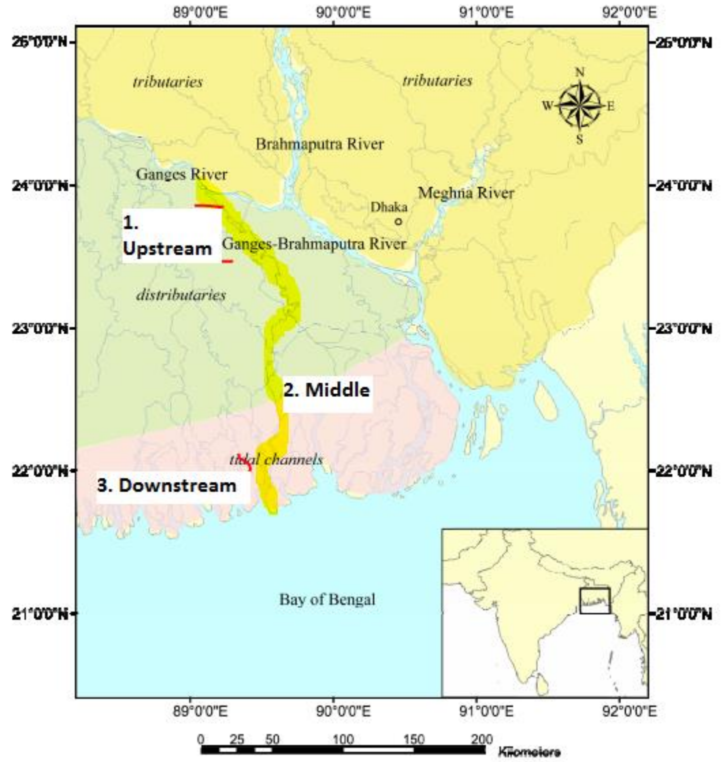

Figure 4 Map showing the different regime classes. Classes are determined for whether water flows from a drainage basin into the main river channel (tributaries) or from the main river channel into the Bay of Bengal (distributaries). The tidal channels class identifies channels in the southern region where saline water intrudes during the tidal cycle (Rice, 2007). Points 1,2&3 are the study sites.

Upstream, the river regime

Gorai is upstream in the delta and is a distributary of the Ganges river. The water regime or water level (figure 5) is controlled by the regime of the Ganges which shows a clear seasonality.

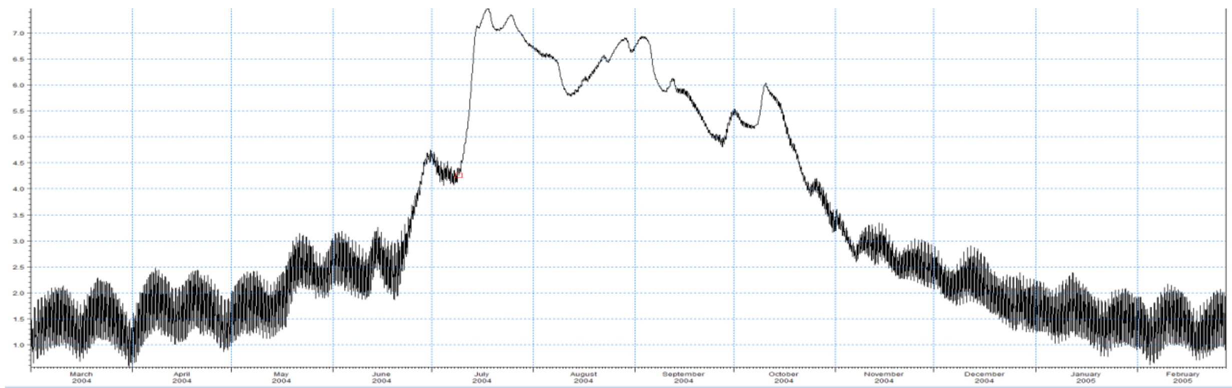

Figure 5 Water level Upstream March 2004 - February 2005. Made from data of the IWM

Four seasons can be distinguished in Bangladesh, dry season (December-February), summer or pre-monsoon (March-May), southwest monsoon (June-September) and autumn or post-monsoon (October-November). In the winter season the temperature is around 18-22 C. Only 2% of the annual rainfall occurs in this period. The mean temperature of Bangladesh during the pre-monsoon vary between 23 and 30 degrees Celsius. In the north- and southwest district temperatures can reach 36 to 40 degrees Celsius. 19 % of the total annual rainfall occurs during this season. The southwest monsoon starts in June. More than 71% of the total annual rainfall falls in this season. This causes the high peak in figure 5. with the high water volume a lot of sediment is pared. Therefore, sediment concentrations are the highest in this season Floods are frequent during this period. In the post-monsoon season, only 8% of the annual total rainfall falls(Khatun et al., 2016)(Hofer et al., 1997).

Downstream, the tidal regime

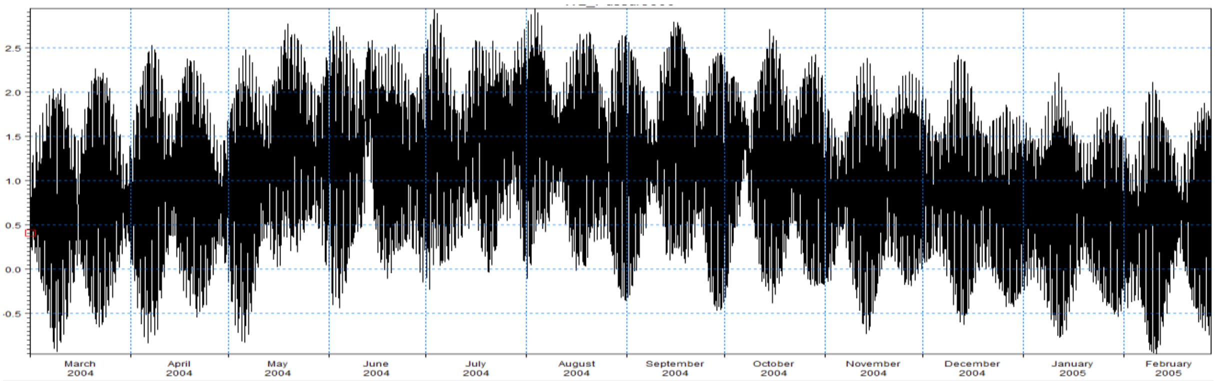

Figure 6 Water level Upstream March 2004 - February 2005. Made from data of the IWM

Pussur is downstream in the delta (figure 4, point 3). The water regime is dominated by tides and has an additional water impulse from the monsoon which can be seen in figure 6 The tidal regime is semi-diurnal, M2. There is one ebb and flood per 12 hour period. which means that there are two times flood and two times ebb a day. The amplitudes of the semi-diurnal tides are not very high, between 1.5 and 3m (figure 6) which is the same as in the Bay of Bengal (Sindhu et al., 2013). Over 80% of the sediment in the system of the Ganges river gets transported via the main channel to the sea. The sediment is taken westwards by the currents and flows back the mainland through tidal channels (figure 8).

Middle, the mixed regime

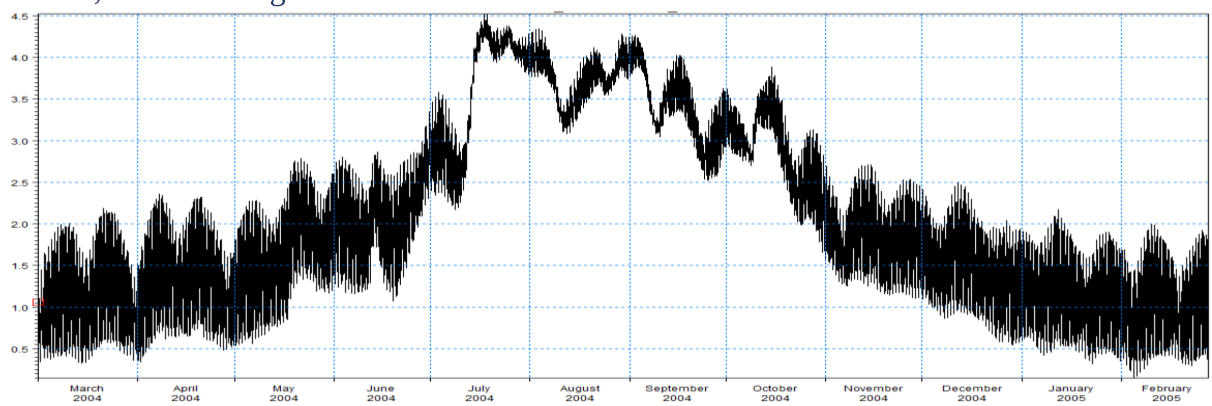

Figure 7 Water level Upstream March 2004 - February 2005. Made from data of the IWM

The centre delta is on the border of the distributaries and the tidal channels (figure 4, point 2). This way it has influences of both the river and the tidal regime. It has got a clear monsoon peak but still is heavily influenced by tides. Tides are not as high as in the river mouth and water levels are lower than in the river regime. The combination of tidal and river influences are well shown in figure 7. The middle of this river

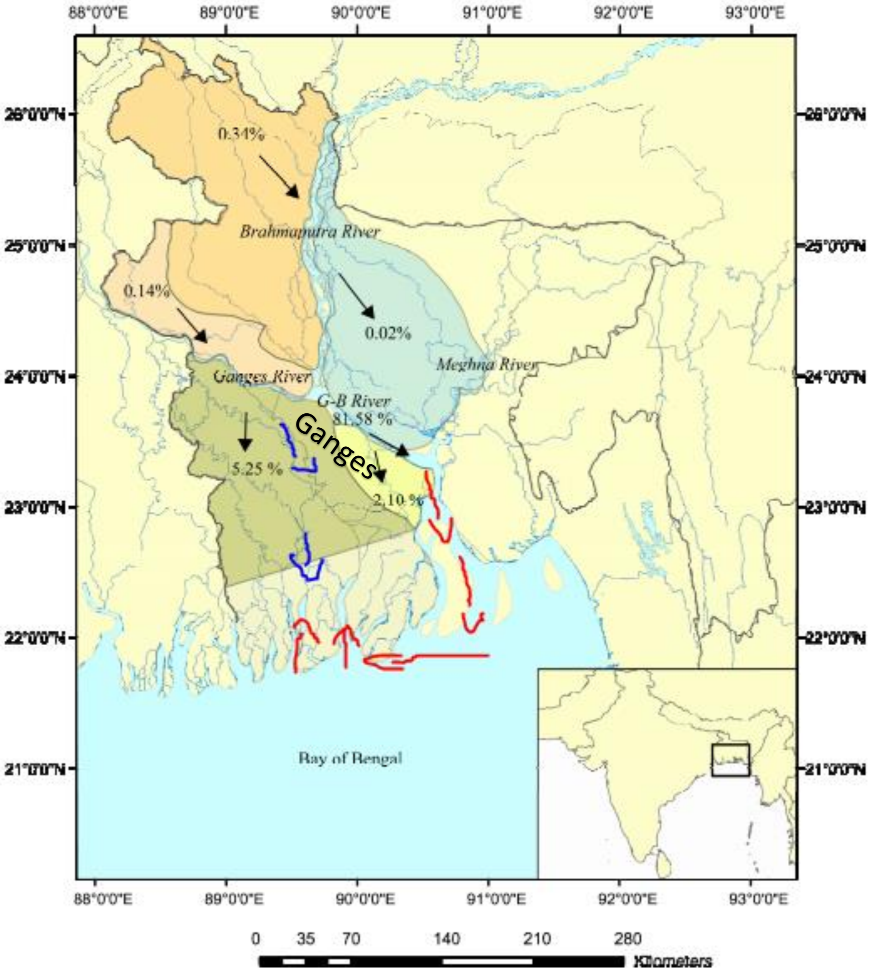

Figure 8 Suspended sediment flow chart of the Ganges-Brahmaputra River System. Percentage values are calculated with the total suspended load in the system as the sum of the Ganges and Brahmaputra rivers' individual loads. Approximately 82% of the sediment from the two individual rivers continues in the Ganges-Brahmaputra main river channel. (Rice, 2007) Blue arrows are the sediment transport through the tributaries, red arrows the sediment transport through the main channel.

3. Method

To calculate the total sediment accumulation and spreading MIKE 21 FM (DHI, 2017), a 2D hydrodynamic model with a flexible mesh (FM) was used. This model is set up and validated for beel Phakimara (Islam, 2019). By entering different input files in the model, scenarios were forged so it was possible to imaginarily move the beel along the delta so the different regimes could be modelled (upstream, in the middle and downstream). The model calculated sediment accumulation and made maps of sediment spreading. A run lasts seven days due to a restriction of modelling time, so there are no full tidal cycles modelled.

3.1 MIKE 21 FM

MIKE 21 FM is based on the solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations. The module uses an approximate Riemann solver to calculate the convective fluxes at the interface of the cell of the 2D mesh.

The Model is set up for Beel Pakhimara. (see study area). More detailed description about the working of the model and MIKE 21 FM are found in Islam, 2019. In the model, the standard settings are the outline of the beel with a digital elevation map and the 2D mesh (figure 9).

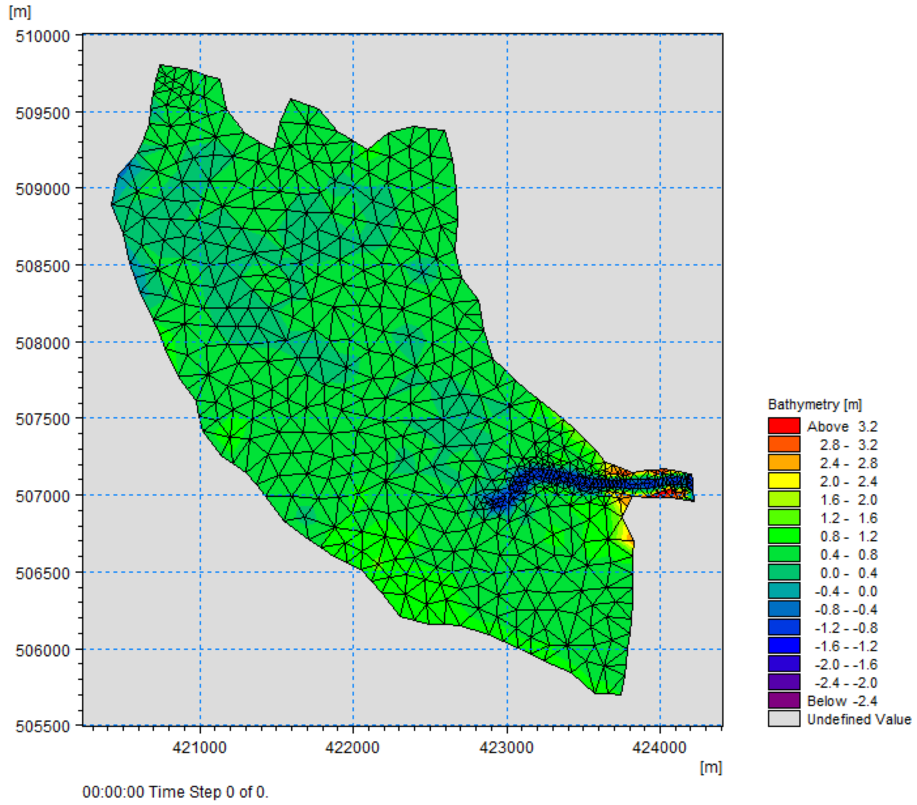

Figure 9 Digital elevation map and the mash for the beel Pahkimara (Islam, 2019)

3.2 Input data

	Time	1:Inlet 1 [()]	2:Inlet 2 [()]
17	16-1-2005 08:30:00	0	1
18	16-1-2005 09:00:00	0	1
19	16-1-2005 09:30:00	0	1
20	16-1-2005 10:00:00	0	1
21	16-1-2005 10:30:00	0	1
22	16-1-2005 11:00:00	0	1
23	16-1-2005 11:30:00	0	1
24	16-1-2005 12:00:00	0	0
25	16-1-2005 12:30:00	0	0
26	16-1-2005 13:00:00	0	0
27	16-1-2005 13:30:00	0	0
28	16-1-2005 14:00:00	0	0
29	16-1-2005 14:30:00	0	0
30	16-1-2005 15:00:00	0	0
31	16-1-2005 15:30:00	0	0
32	16-1-2005 16:00:00	0	0
33	16-1-2005 16:30:00	0	0
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39	16-1-2005 19:30:00	0	0
40	16-1-2005 20:00:00	0	0
41	16-1-2005 20:30:00	0	0
42	16-1-2005 21:00:00	0	0
43	16-1-2005 21:30:00	0	0
44	16-1-2005 22:00:00	0	0
45	16-1-2005 22:30:00	0	0
46	16-1-2005 23:00:00	0	0
47	16-1-2005 23:30:00	0	0
48	17-1-2005 00:00:00	0	0
49	17-1-2005 00:30:00	1	0
50	17-1-2005 01:00:00	1	0

Figure 10 example of a part of a gate operation file

To reconstruct the different regimes three sets of data were used. A set consists of a water Level- (WL), a suspended sediment concentration- (SSC) and a gate operation file. The data was gathered from reports and the database of the Institute of Water Modelling (IWM). The WL and SSC files are a combination of with the hand-collected dataset for de upstream and downstream regime and two interpolated files for the middle regime. This was done because of a limitation of available data. All the files have data for every half hour. Gate operation files are the files that control the gates. They can open and close a gate (figure 10, 0 is closed 1 is open). With these files, the scenario's in table 1 (*3.3 scenario's*) were made. Six operations are modelled during three seasons. Pre-Monsoon (pre), Monsoon (mon) and Dry-season (dry). These are the three annual moments that differ the most and thus give a good representation for a year. The start dates (table 2) for the model are a derivate from the water level graphs (figure 5,6 and 7) and where chosen on a representative moment of the season. The duration of 1 run is 7 days and was run for every half hour so 336 steps in total. This duration was chosen to limit the running time of the model. A known problem is that 7 days is not a full Spring and neap tide cycle, which is 14 days, and therefore misses data. Also, all data is from one year and not the averages over multiple years so data outliers will be present in the results.

3.3 Scenarios

In total 54 different models have been run. This is a result of different combinations of input files that represent the different regimes and seasons. The total of 54 is built up out of three parts. Firstly, There are two inlets in the polder, one in the northwest and one in the southeast with gates that can be opened and closed separately. This way 6 different operations are distinguished, see table 1.

Table 1 The different gate operations and their name

Nr.	Operation	Name
1.	Both gates are open during the whole running period	1-2 open
2.	Gate 1 and 2 are operated parallel and are dynamic during the running period. E.g., gate 1&2 are both open and after 12 hours both gates close.*	1-2 parallel
3.	Gate 1 operates dynamic and 2 is closed during the running period. E.g., gate 2 is always close but gate 1 opens for 12 hours and then closes for 12 hours*	1-dynamic 2- closed
4.	Gate 1 is closed and 2 is operated dynamically during the running period. E.g., gate 1 is always close but gate 2 opens for 12 hours and then closes for 12 hours*	1- closed 2- dynamic
5.	Gates 1 and 2 open alternating. E.g., gate 1 opens first for 12 hours and 2 is close. Then 1 and 2 are closed for 12 hours and next 2 opens for 12 hours.*	1-2 alternating
6.	Gates 1 and 2 open alternating. E.g. gate 1 opens first for 12 hours and 2 is close. Then 1 and 2 are closed for 12 hours and next 2 opens for 12 hours.*	2-1 alternating
*Opening and closing of the gates are depending on gate operation files in connection with the tidal cycles		

Secondly, the application was then run on the three different areas: upstream, middle and downstream (see study area). Lastly, for the different seasons: Pre-monsoon, Monsoon and Dry season. The start dates of these seasons are shown in table 2.

Table 2 Start dates of model run in dd-mm-yy hh:mm

Start-dates	Pre-monsoon	Monsoon	Dry
Upstream	21-04-04 21:00	13-07-04 00:00	17-01-05 00:30
Middle	21-04-04 05:30	13-07-04 01:30	16-01-05 21:00
Downstream	22-04-04 00:30	13-07-04 08:30	17-01-05 04:00

3.4 Output

Output data of the model is sediment accumulation is in grams per square meter. This outcome is then multiplied with the total area of the polder in ArcMap so that the final result is in grams. Before graphs were made, the outcomes are converted into tons. The model also creates maps which show the distribution of the sediment within the polder. Next, graphs were made which show the total sediment accumulation in tons.

4. Results

the water level and suspended sediment graphs are shown in figure 11A-I. The left axis is the SSC in g/L and the right axes displays WL in meters. SSC is shown in blue lines and orange the WL. The duration of the graphs is precisely seven days. Also, figure 14 shows the total sediment accumulation in tons for the different locations.

4.1 Available sediment

Upstream

See figure 11A-C. The WL and the SSC of the upstream regime are dominated by seasons. During the Monsoon water influx from the Himalaya is increased and causes a high WL, up to 7.5 meters, and an SSC of almost 0.4 g\l. In the pre and dry season, there is less water available, and the WL changes between the 1 and 2 meters. Sediment concentrations in the pre-monsoon are between the 0.1 and 0.25 g\l and in the dry season between the 0.07 and 0.22 g/l. In the monsoon, tides have no effect and cause a constant water level. In the pre-monsoon and dry season the tidal amplitude is around 1 meter. Also, an asymmetric ebb flood cycle is shown this means that flood enters the channels faster than it leaves during ebb. In this regime, spring or neap tides are not applicable. Differences in water level and suspended sediment concentration between pre-monsoon and dry season are very little in contrast with the monsoon.

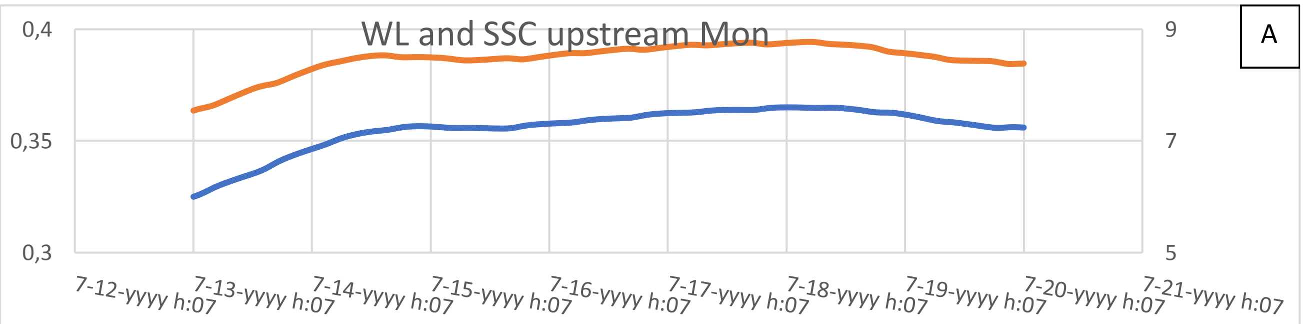
Downstream

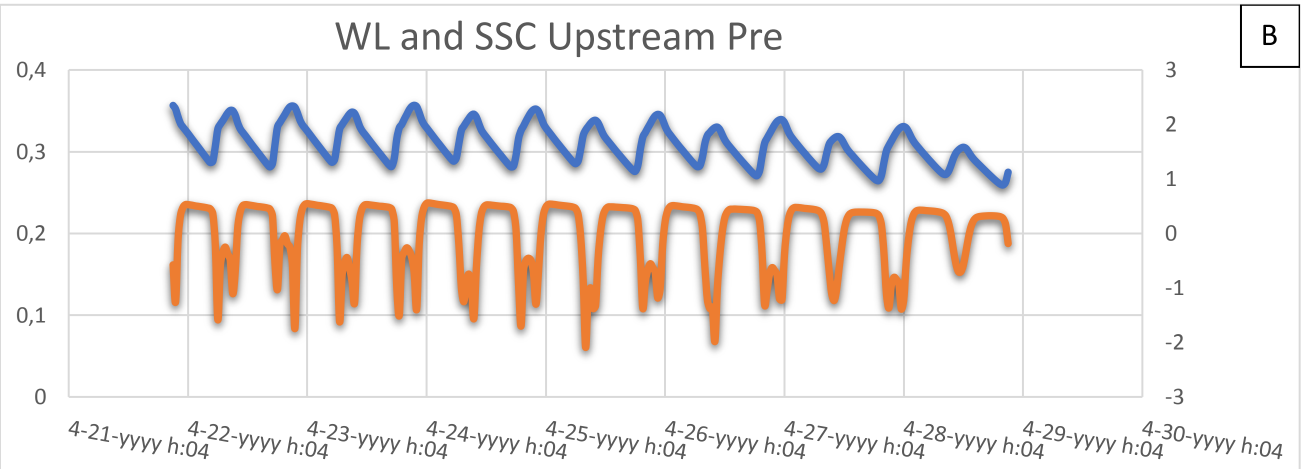
See figure 11D-F. In the downstream area, WL is influenced by tides constantly. During the seven day period of the pre-monsoon is becoming neap tides because water level starts between -0.3 and 2 meters and decrease to 0.2 and 1 meter. The sediment concentration changes with the WL from 0.16-5.4 g/l to 0.14-1 g/l. In the monsoon it is becoming springtide with WL's starting at 0.75-1.7m increasing in amplitude to 0.17-2.5m. SSC are 0.17-0.4 which becomes 0.2-2.6 g/l. The dry season has a period where the neap tides lowest point is in the middle of the period. Beginning and end WL's are the same magnitude: -0.2-1.5 m and when the water level is at the lowest they differ between 0.0 and 0.9m SSC correspondend as well: 0.2-1.8 on the highest points and 0.17-0.78 when the neap tide is at his strongest.

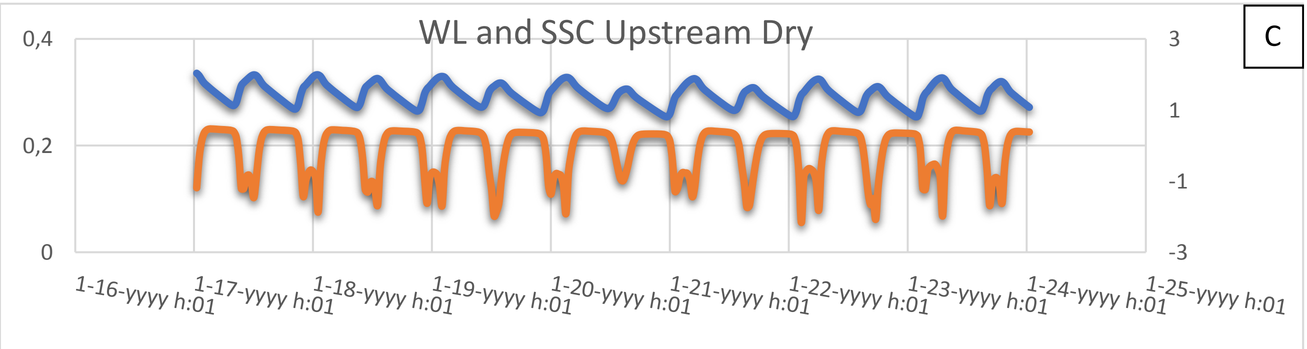
The more significant the amplitude the faster the water flow through the channels and the higher the suspended sediment concentration will be. Although water levels are lower in the monsoon than in the river and mixed regimes, the suspended sediment concentrations are higher. The monsoon graph does not differ so significantly from the other two seasons in this regime but has a relatively low concentration in comparison with the amplitude and water level.

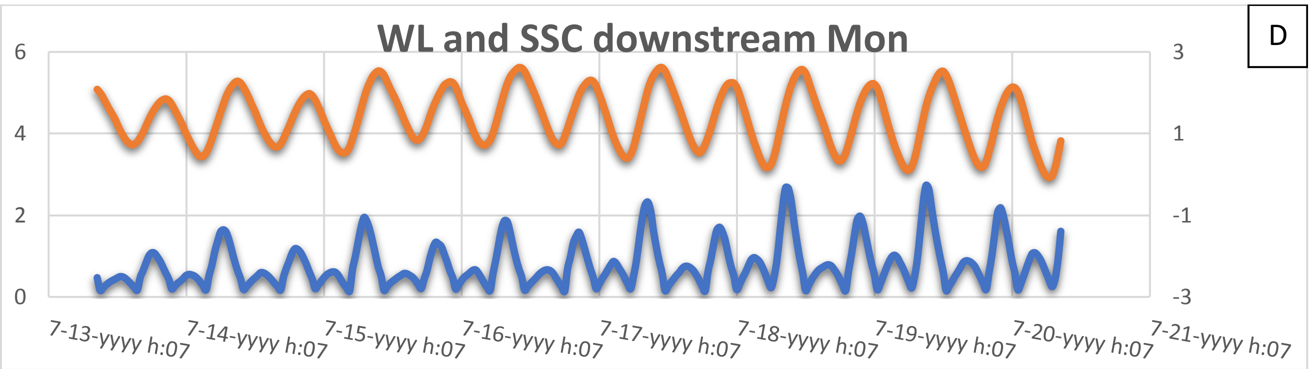
Middle

See figure 11G-I. In the mixed regime (the middle of the river) tides still play a role. In the monsoon, this role is the smallest with an amplitude of 0.3m. the WL is around 4m, SSC is dependent here on the water level and is ~1.5 g/l. Pre and Dry Season are again of the same magnitude. WL: 0.5-1.4m and SSC 0.2-0.7 g/l. The amplitudes are not as high as in the tidal regime but they are present in all three of the seasons, so a change in the monsoon in comparison with the river regime. Also an asymmetric ebb and flood cycle is shown.





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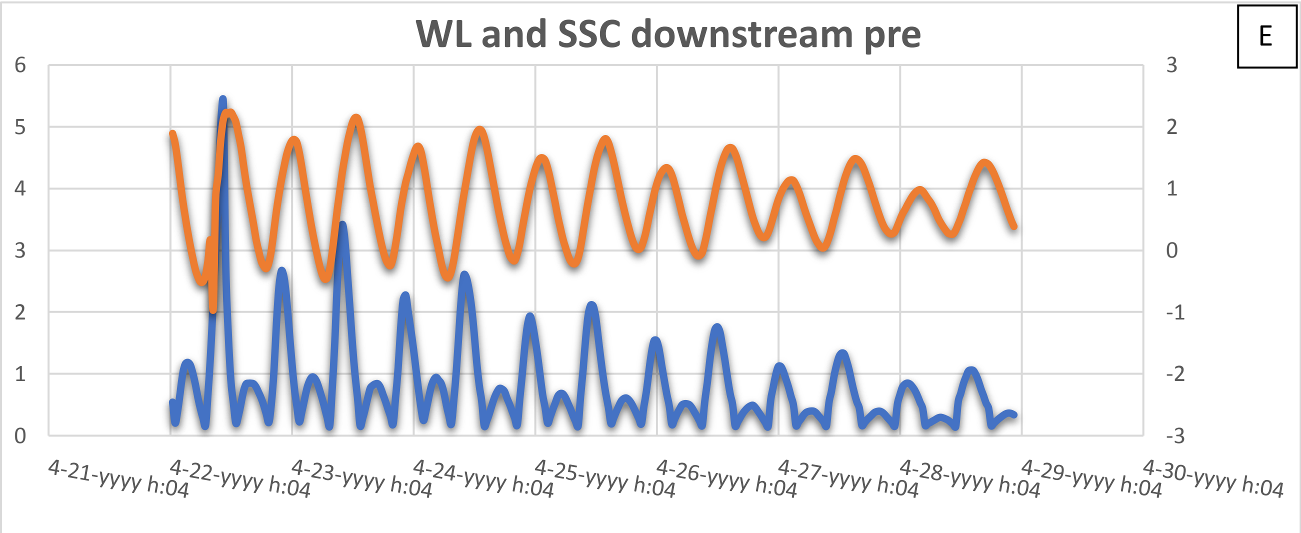
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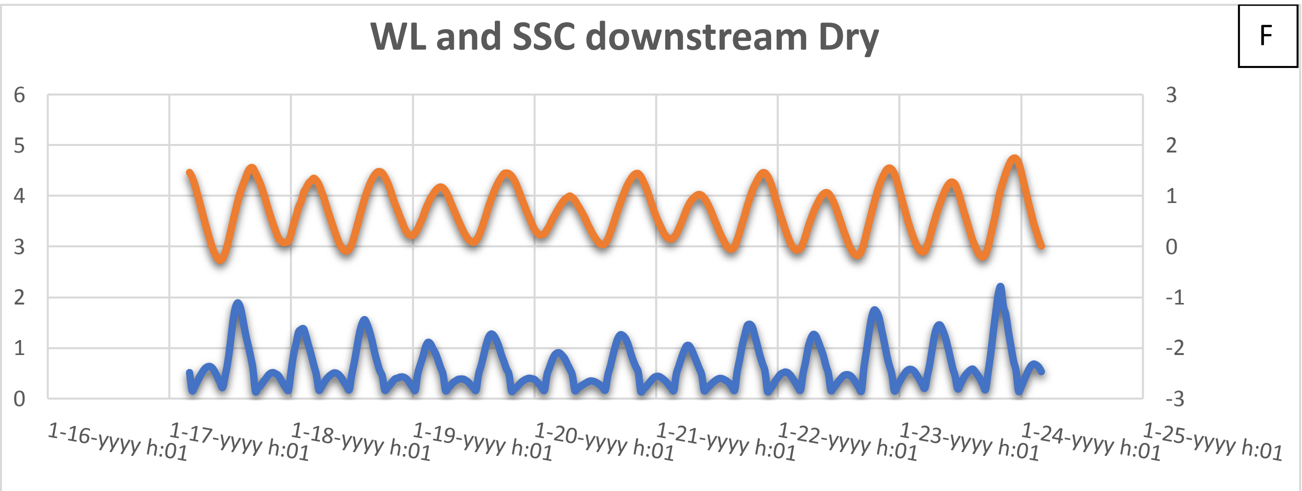
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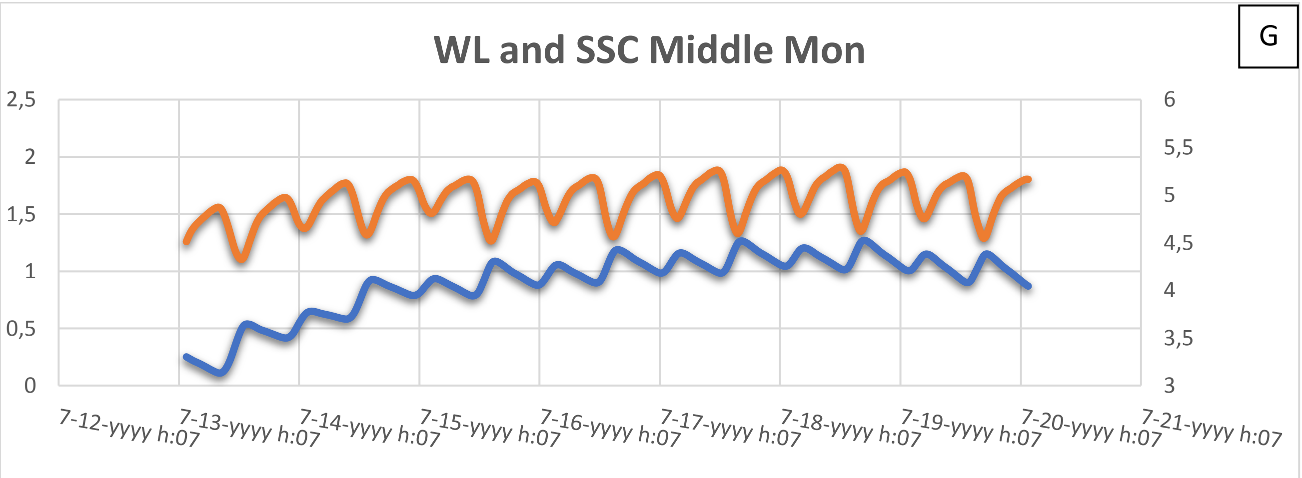

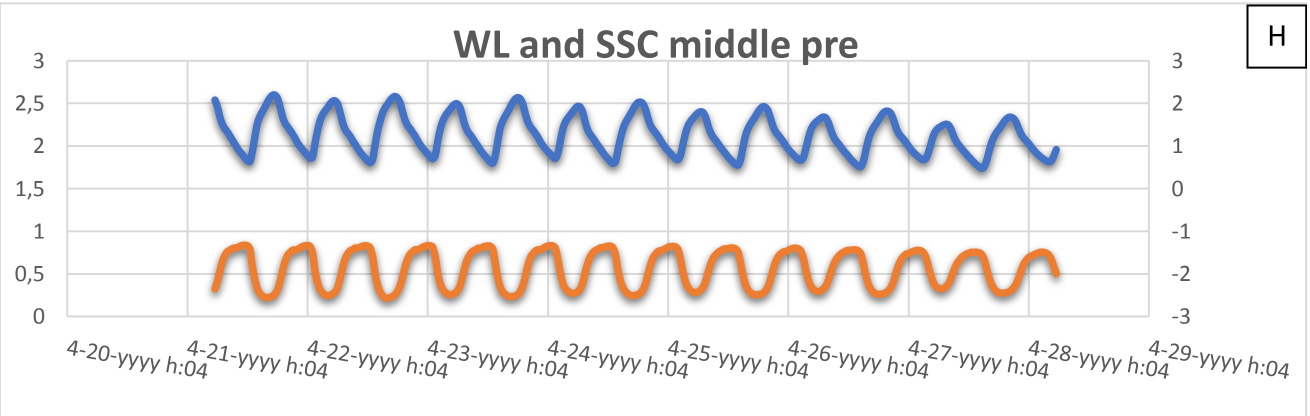

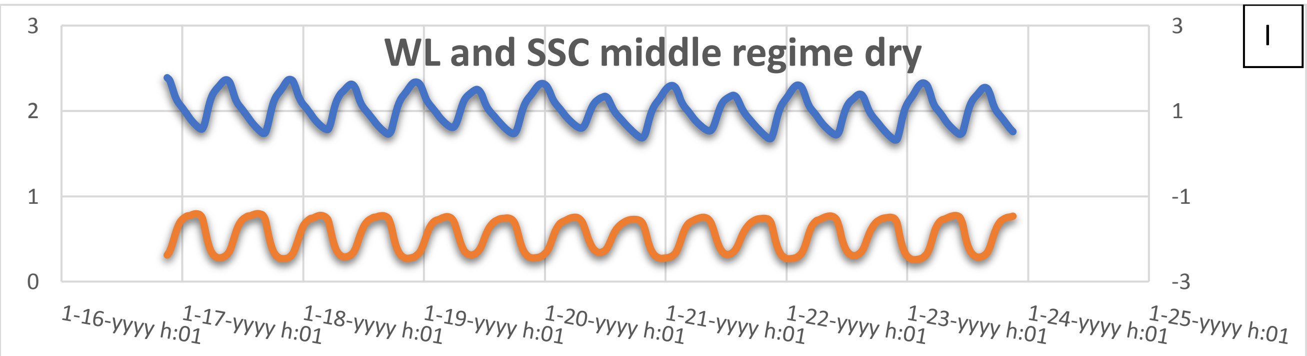

Figure 11 A-I. Water level and suspended sediment graphs from data of the IWM

4.2 Spreading

Each of the different gate operations have an effect on the spreading of the sediments within the polder. Figure 12 are maps of four different gate operations and show the total accumulated sediment calculated and shown. These maps are made with the downstream, monsoon data were 1-2 and 2-1 alternating give similar spreading like wise for 1-dynamic 2-close and 2-dynamic 1-close so only one of each of this similar operations is displayed. When there is only one gate, spreading is minor relative to two gates (figure 12A has only one gate). Sediment enters the polder only at one side and cannot distribute far enough in the polder. With two gates, sediment enters from both sides and sediment gets accumulated evenly throughout the polder.

In general, when the two gates work together, so open and close at the same moment (1-2 parallel, figure 12D), the spreading is the most homogenous.

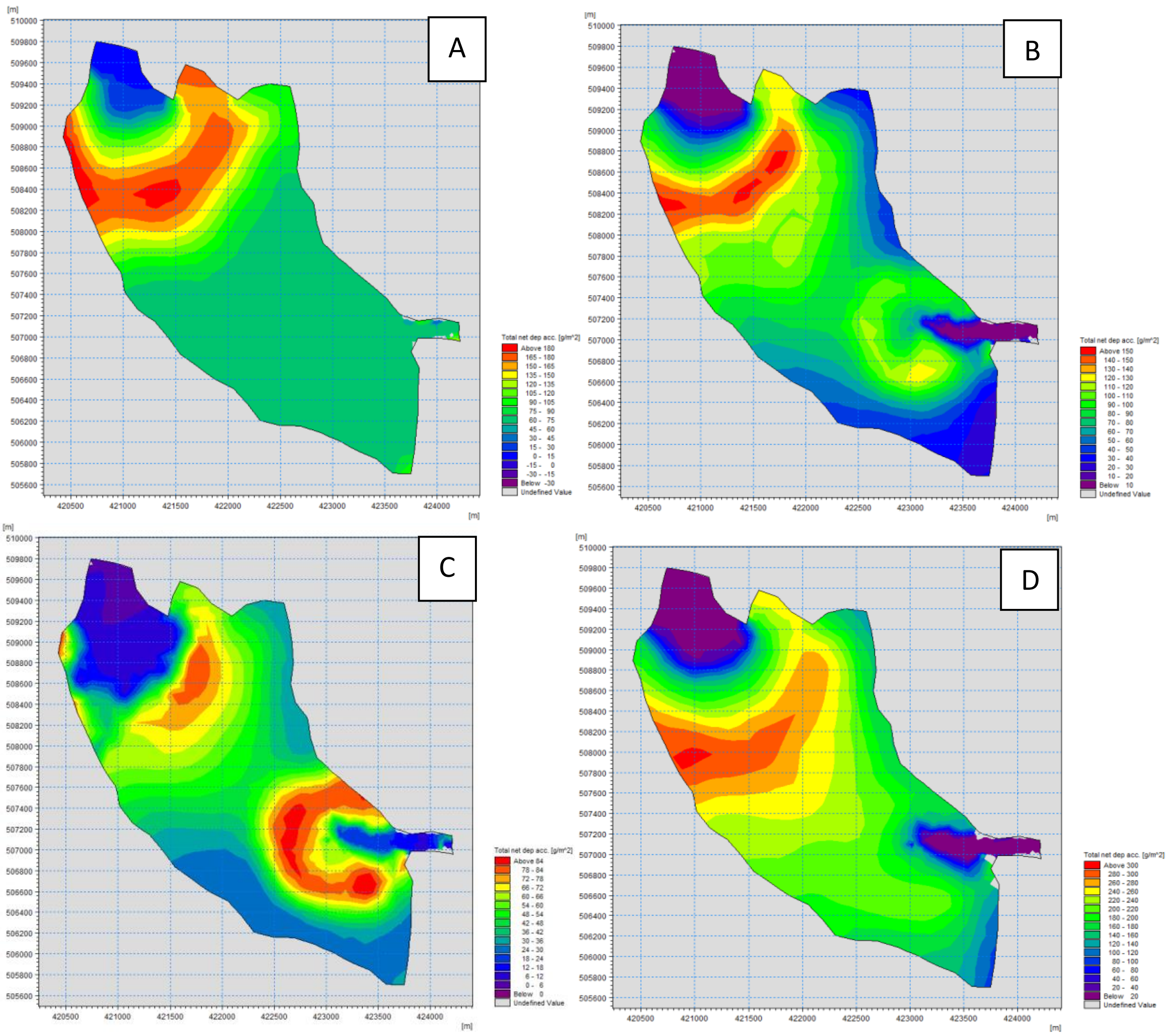

Figure 12 Spreading of sediment. for different operations. A: 1-dynamic 2-close, B 1-2 Alternating, C 1-2 open, D 1-2 parallel

4.3 Sediment accumulation

Upstream

See figure 13A. In the upper part of the delta, sediment accumulation differs significantly between seasons. However, within the seasons the gate operations have minimal effect on the total sediment accumulating in the polder. In the monsoon when water level and SSC are at its highest accumulation is between 100 and 120 tons depending on the gate operation. Operation with only one gate gives the highest values of all. When there are no gates in the polder, the total sediment accumulation is the lowest gaining scenario in the monsoon. In the pre- and dry-season the total sediment accumulation does not reach more than 20 tons. Here again the operations with just one gate generate the most.

Downstream

See figure 13B. When the regime is dominated by only tides, the total accumulation becomes dependent on the interaction between the gate operation and the water level and suspended sediment concentration. The monsoon is no longer the period with the most accumulation of the three seasons. Sediment accumulation is more evenly spread throughout the year with a peak in the pre-monsoon when two gates open and close at the same time. The accumulation then peaks with over 1700 tons, which is around 15 times as much as the highest values in the upper delta. In this season operations with two gates trapped 5 to 8 times more sediment in the polder then with one gate. Also, an surprising result is that when the polder has no gates accumulation can reach up to 1500 tons. And not only in pre-monsoon this scenario has this order of values but also in the monsoon the scenario can the total accumulation reach 1400 tons. This is the highest value in this season and is far more efficient than scenarios with gates. In the dry season, values are a bit more tempered. The overall values lie between 380 and 780 tons. Likewise as in the upper delta de scenarios with one gate only give the most sediment accumulation.

Middle

See figure 13 C. Like in the upper delta the monsoon causes the highest deposition rates in the central delta. When the gates open and close simultaneously and when one gate is dynamic and the other is closed, accumulation rates can go up to almost 1800 tons and these are the highest values of all. The scenario where there are no gates is surprisingly effective in this area. In particular, in the dry and pre-season these operations are the most efficient and thus get the highest values in the dry and pre-season. Noticeable is that there is a big difference between the two single dynamic operations in the monsoon because when compared to the other regimes the values deviate from what has been observed in the other regimes.

4.4 Discharge

The in- and outflow of water with sediment in the polder is also related to the total accumulation. In the upstream part the water flux in and out changes multiple times within the time period that the gates are open (figure 14A). This causes very high flow speeds and sediment resuspension. Also, half of the time water is flowing out of the polder. In the center part, the water flow is more composed (figure 14B). When the gates open water enters the polder and this continually keeps on going till the ebb starts. In the downstream area the discharge is equal to the tidal cycle this is a relatively smooth transition (figure 14C).

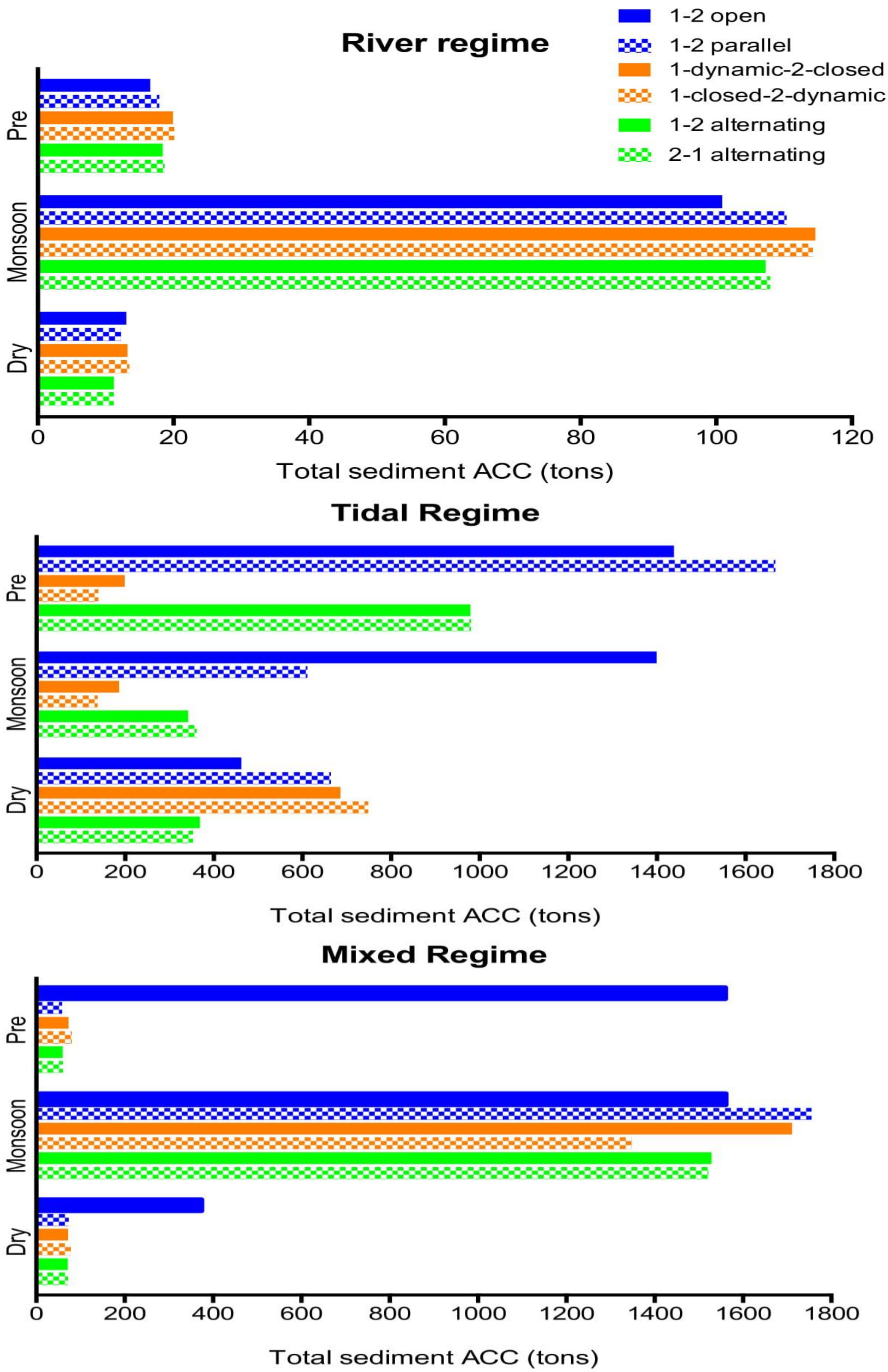

Figure 13. Total sediment accumulation charts

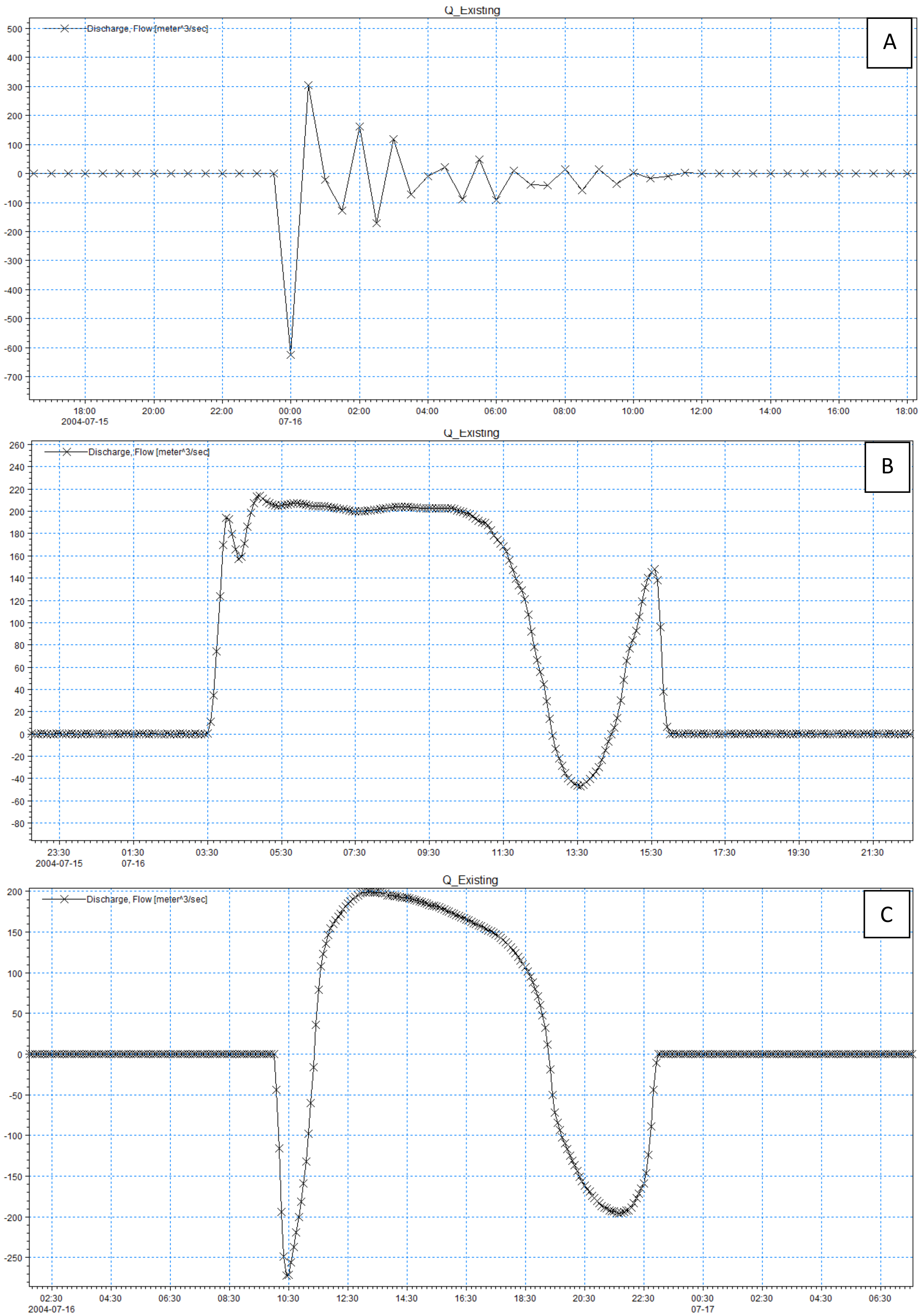

Figure 14 waterflow in and out of the polder

5. Discussion

Upstream

To catch the most sediment in a polder upstream of the river the season has the most significant influence. The monsoon, which gives water levels up to 8 meters brings so much more sediment than the other seasons. This sediment originates from the Himalaya with sediment transportation and by sediment resuspension by the water flow. The differences are of such a magnitude that regulating the sluices in the pre-monsoon and dry period do not have a significant effect. In the monsoon, the gate operations have little to no effect in contrast with each other on the total sediment accumulation. This could be a result of the discharge behaviour upstream, the fast in and outflow of the water causes many resuspensions and does not give the sediment time to settle and deposit. Gate operation does not influence the accumulation because almost all the water that comes in the polder also goes out. The small variation in total accumulation could be caused by the moment of opening and closing a gate and the WL and SSC at that specific moment. This also explains why accumulation rates are so low in this part of the tributary.

Despite that, the operation without gates does not have the highest accumulation, this is the cheapest and easiest scenario. For this scenario either no gates will be built or gates could be built and only have to be operated a few times per year (maybe more for extreme water levels). It would be recommended only to use the gates in the monsoon period. So the polder can be used for agriculture in the other two seasons.

Downstream

The tides have a significant positive influence on the total sediment accumulation. Values are up to 15 times as big than in the river regime. The explanation can be found in the sediment availability. The sediment enters the area from two sides (figure 8) but mostly from the south due to the sediment flow and the tidal influences which can intrude sediment till 150km land inwards. The more significant part of the sediment mainly follows the main channel, in this case, the Ganges and enters the Bay of Bengal. With the west directing currents, sediment gets transported along the coast. By tides, water with sediment enters the Pussur river and delivers a tremendous amount of sediment. The rest of the sediment contributes from the north.

When the seasonality is not the biggest influencer of sediment accumulation anymore, gate operation plays a vital role to trap sediment. Overall, the scenario where two gates operate in parallel is the most efficient gate operation, especially in the pre-monsoon. In the pre-monsoon, the total sediment accumulation is around 1700 tons. This is very high and can be related to the sediment availability in combination with the discharge pattern. There is much water with an enormous amount of sediment entering the polder relatively calmly. The outgoing water is less than the incoming. In this area, gates can be operated throughout the whole year. Each season has its own best operations and operating the gates should be done in consultation with the farmers in the area and be based on the preferences of all the stakeholders who are involved in the TRM for the area.

In the pre-monsoon gate operation 1-2 parallel, where the two gates work with each other is the most efficient. This could be explained by the input data within the model as well. Suspended sediment concentration start high in the pre-monsoon and with a low starting water level within the polder all the sediment can enter the polder. Due to the discharge behaviour most of the sediment stays behind.

In monsoon, the scenario without gates has the highest values. The constant in and outflow of water, with a positive net accumulation rate, causes a total accumulation of 1400 tons. An advantage of this scenario is that the gates do not have to be operated. A disadvantage is that there is less control. The remaining operations are inefficient in comparison to the scenario without gates, which is counterintuitive because in the monsoon the sediment availability should be at the highest and the other accumulation rates should be high too. It could be possible that the highness of the total accumulation could be related to the first suspended sediment concentration that enters the polder. In the pre and dry- period these values are higher and also give higher accumulation rates.

In the dry season, the two gate operations where only one gate is opened are delivering the best results. Because there is only one gate, the water escapes the polder slower than with two gates. This explains the values. On the other hand, give the operation heterogenic spread and do not lift the entire polder (figure12).

Middle

The mixed regime is a real mix between the up- and downstream regimes. Same as the river regime the mixed has a clear seasonality where monsoon is the season delivers the most sediment accumulation. Far more than the pre and dry periods where accumulation is insignificantly low relative to the monsoon. However, with the same or even more sediment availability as the downstream regime, values can reach up to almost 1800 tons of sediment accumulation during monsoon.

To get the most evenly spread accumulation, again, the scenario with two gates which work together is the most efficient.

6. Conclusion

The goal of this thesis was to find out whether TRM can help against the further decline of the area and at the same time resolve the silted up rivers and bring back nutrients is the polders. The results have shown that managing water through sluices can add up to 1800 tons of sediment in 7 days. By researching multiple gate operations, it has been clarified that not one specific gate operation is 'better' than other gate operations. Instead it has become clear that the best operation for a polder depends on its place within a delta and the season. the main conclusions are:

- Upstream of the river monsoon is the best season to operate the gates. Operating sluices in other seasons will not contribute to an elevated polder. Different gate operations have little effect on the accumulation so the operations should carefully be picked in correspondence with local stakeholders.
- In the middle, the monsoon is the best season as well. Accumulation values are the highest seen over the whole research area. This is because of discharge behaviour and the total suspended sediment concentration availability.
- Downstream seasonality is not the most important factor anymore. Flooding of the polder could be done throughout the whole year. Not operating the sluices or two gates that operate simultaneously are overall the best scenarios.
- Using two sluices gives a more uniform spread of accumulation and is preferred.

Even though the results show a positive view, decisions of which operation should be used must always be done with all the stakeholders present. The results are model estimates, and there are still many uncertainties. Further research has to be done looking at more extended running periods of the model understands sediment behavior if gates stay open for example a whole season and if the effects of the gates are not only in the feasible in the starting period of opening the gates.

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